Space-Charge Compensation of Proton Beams with Trapped Electron Columns from Beam-Induced Rest-Gas Ionization

Giulio Stancari

Accelerator Physics Center
Fermi National Accelerator Laboratory

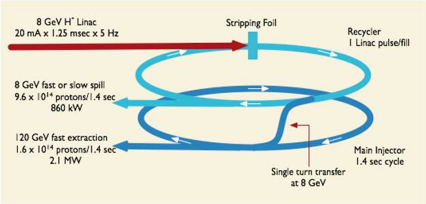
Tevatron Accelerator Studies Workshop
Fermilab
January 13–14, 2010

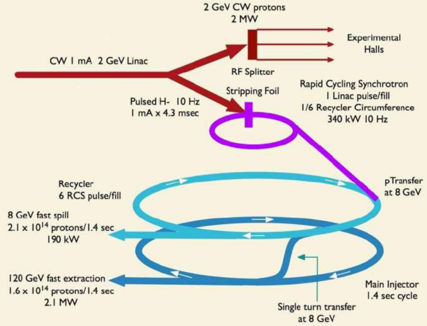
In collaboration with

- Y. Alexahin, V. Shiltsev, A. Valishev (FNAL)
- G. Kuznetsov, A. Romanov (BINP Novosibirsk)
- A. Kabantsev (UCSD)

Motivation

- Fermilab's plans to lead accelerator-based neutrino and flavor physics in the next decade rely on the construction of a multi-MW proton source: Project X
- Stepping stone towards future neutrino factory, International Linear Collider or muon collider
- Two designs are being considered:





- One performance limitation is trade-off between linac cost ($\propto \gamma$) and beam losses and activation due to space charge in synchrotron ($\propto 1/\gamma^2$)

Effects of beam space charge

- Space-charge forces in a beam arise from mutual Coulomb repulsion ($\propto \gamma^0$), cancelled in part by magnetic attraction ($\propto -\beta^2$)
- These forces limit intensity because of phase-space dilution, beam losses, and radioactivation of components
- In synchrotrons, losses depend on space-charge defocusing tune shift:

$$\Delta\nu \propto -\frac{N r_0}{\beta\gamma^2\epsilon_n}$$

		tune shift	injection losses
Currently:	Booster	-0.30	15% or 300 W
	Main Injector	-0.03	1% or 200 W

- For a given level of tolerable losses, compensation of space charge means higher intensities can be achieved
- Reduced space-charge tune spread may make slow spill possible

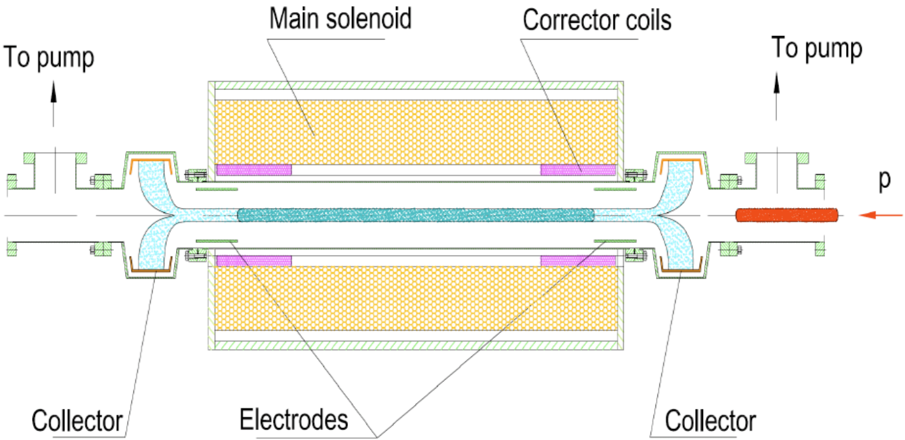
Requirements for space-charge compensation

- Coulomb repulsion can be mitigated if circulating protons are forced through a nonneutral plasma column of opposite charge
- Because the column is at rest in the lab frame, required charge density is (proton density)$/\gamma^2$ for full compensation.
- At 8 GeV, $1/\gamma^2 = 1/90$: $1/90$ of charge density over whole ring, or same charge density over $1/90$ of ring.
- For 8-GeV Project-X MI, need $N_e \sim 10^{12}$, $n_e \sim 10^{10}$ cm^{-3}
- Column density should have same transverse profile as beam

Proposed solution:

With solenoid and electrodes, trap electrons from rest-gas ionization caused by the beam, constraining them to the radial position where they were generated

Electron column concept



Shiltsev, PAC07

Electron column design

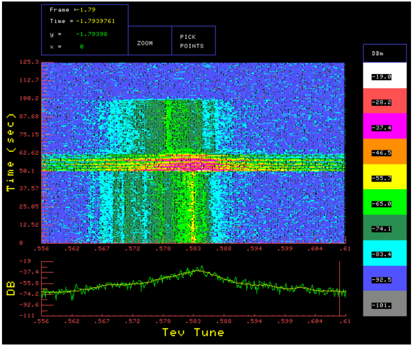
- Length: 2 m
- Solenoidal **B** field: 3 T
  - Larmor radius of ionization electrons $\ll$ proton beam transverse size $\Rightarrow$ column mimics transverse beam density
  - enhances radiation cooling
  - stabilizes column
- Electrode voltage: 5 kV to trap enough charge
- Ionization cross section: 2×10^{-19} cm^2 (8-GeV p in H_2)
- Average ionization rate in trap: 7×10^9 (ion pairs)/μs (3 A of 8-GeV protons in MI, 10^{-8} mbar)
- Crossed-field ($\mathbf{E} \times \mathbf{B}$) plasma rotation around axis requires round beam at column locations

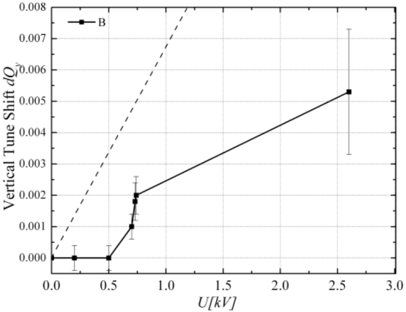
Issues

- Positive ions cause instabilities, must be free to leave trap
- Solenoid introduces coupling $\Rightarrow$ skew quads, or columns with opposite fields
- Column can generate β beat; better to locate one in each superperiod
- Stability of beam-column system?
- Trap lifetime?

Preliminary experiments in Tevatron at 150 GeV

- Used existing TEL solenoid and electrodes



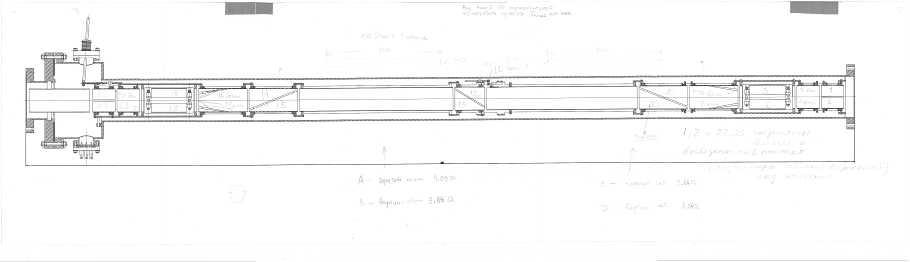


- Observed positive tune shifts vs electrode voltage above 5×10^{-8} torr
- Vacuum instabilities and beam loss

V. Shiltsev et al., PAC09

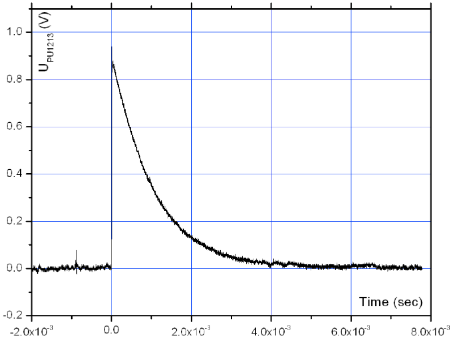
Preliminary experiments in test bench

- 0.1–10-keV electrons as primary beam
- Solenoids at 0.1–0.4 T
- BPM plates used as confining electrodes
- central electrodes as pickups



Preliminary experiments in test bench

- Observed charge flow on central pickup when opening trap



- In magnetic bottle configuration (4–1–4 kG) and no confining electrodes, observed plasma oscillation frequencies on spectrum analyzer (work in progress!)

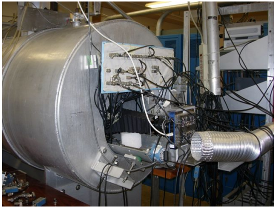
Related fields

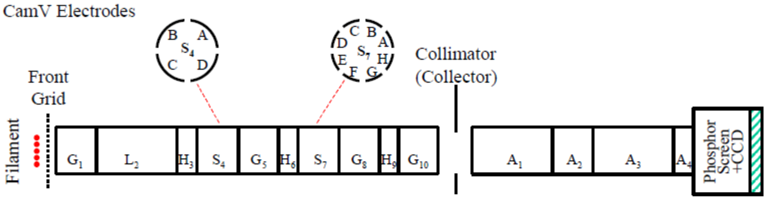
Project can benefit from interaction with related fields of expertise:

- Tevatron electron lenses
- Electron cooling
- Electron-cloud effects
- Ion instabilities in klystrons and traveling-wave tubes
- Nonneutral plasmas:
  - estabilished collaborations with experimental and theoretical groups: A. Kabantsev, C. F. Driscoll, T. O'Neil, D. Dubin (UCSD), L. Schächter (Israel)
  - setting up plasma simulations with Warp: R. Cohen, A. Friedman, D. Grote, J.-L. Vay (LBL)

Measurements with CamV at UCSD

- Visited nonneutral plasma group at UCSD to make measurements on trapped electron columns





- Excitation and detection of longitudinal and azimuthal ('diocotron') plasma modes in pure electron plasma
- Measured effect of slow ions on stability of diocotron modes

Ideas from UCSD group

- Configure electrodes to flush ions
- Use plasma frequencies for diagnostics: density, radius
- Magnetic field stabilizes column. Slow-ion instabilities studied at UCSD do not apply to effect of fast protons on column
- Assess whether previous work by R. Pollock at IUCF and P. Colestock at Fermilab is applicable

Pollock et al., AIP Conf. Proc. 498, 336 (1999)

- Instead of using electrons from ionization, inject electrons and let them thermalize? Should be able to obtain desired transverse profile. Thermalization time is of the order of

$$\tau \approx (1\ \mathrm{s}) \left(\frac{10^7\ \mathrm{cm}^{-3}}{n} \right) \left(\frac{T}{1\ \mathrm{eV}} \right)^{1/2} \left(\frac{B}{0.4\ \mathrm{kG}} \right)^2$$

Dubin and O'Neil, Rev. Mod. Phys. 71, 87 (1999)

Research plan

- Theory and simulations
  - study the physics of e-column formation and its stability
  - extend existing Booster simulations* to evaluate effects in MI and RR
- Test-bench experiments
  - measure charge accumulation and stability vs energy, intensity and time structure of beam; magnetic field; electrode voltage; and residual-gas pressure
  - upgrade setup with plasma diagnostics
- design experiments for Tevatron at 150 GeV (this workshop)
- if succesful, design and build prototype for 8-GeV protons in MI or RR; aim at installation during shutdown after Run II

* *Y. Alexahin and V. Kapin, Beams-doc-3108 (2008)*

Tevatron studies with protons at 150 GeV

Experimental goals

- find stable electrode configuration
- detect charge accumulation
- measure tune shifts vs beam intensity, electrode voltage, residual-gas pressure

- Proton-only store
- Existing TEL apparatus
- Will try to use available study time during Run II
- For dedicated run, foresee 4 8-hour shifts

Thank you for your attention